ARMY MATERIEL COMMAND

US ARMY COMBAT SYSTEMS TEST ACTIVITY

US ARMY MATERIEL COMMAND
ACTION COMMITTEE FOR SYSTEM SAFETY

ASSESSMENT, FAULT TREE ANALYSIS AND SOLUTION OF AMMUNITION KICKOUT PROBLEM

TECHNICAL REPORT NO. 90-4

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A study was conducted by the U.S. Army Combat Systems Test Activity at Aberdeen Proving Ground, MD to define ammunition kickout and the mechanisms that lead to its occurrence. A literature search and a fault tree analysis were conducted. It was concluded that a round of ammunition can be kicked out only when a complex sequence of events occurs, also the risk associated with kickout can be mitigated by selectively controlling hazards identified in the fault tree. It was recommended that the operational restrictions imposed test facilities be re-assessed in view of the findings of this investigation.

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TABLE OF CONTENTS

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FOREWORD

The U.S. Army Combat Systems Test Activity (USACSTA) located at Aberdeen Proving Ground (APG), MD, was responsible for planning, researching, conducting, and reporting this investigation. Funds were provided by the U.S. Army Test and Evaluation Command RDTE (D625) Methodology Improvement Program.

A special appreciation is extended to Messrs. Martin Mossa, William Watson, and Rodolfo Gil from the USACSTA Safety Office. Their support in running the computer model to determine the cut sets and single point failures was important to the successful completion of this project. The authors would also like to acknowledge the contributions of Mr. Harry Reeves and Dr. Philip Howe from the U.S. Army Ballistics Research Laboratory (USABRL), APG, whose insights helped focus and guide the technical considerations of this report. The computer modeling in this report was accomplished using Fault Tree Analysis using Personal Computers version 6 August 1987 developed by Jack Copeland.

This report was developed for the Research and Development Subcommittee of the Army Materiel Command (AMC) Action Committee for System Safety by the U.S. Army Combat Systems Test Activity (USACSTA) personnel at Aberdeen Proving Ground (APG), MD. The authors of this report are: Mr. Richard B. Shipe, and Mr. Thomas A. Lucas, USACSTA.

SECTION 1. SUMMARY

1.1 BACKGROUND

a. General. The mission of the U.S. Army Combat Systems Test Activity (USACSTA), Aberdeen Proving Ground (APG), MD, includes the assessment of large caliber weapons. As these weapons increase in size, so does the danger associated with testing them. This problem is experienced not only at APG but also at other installations in the Department of Defense (DoD) where live fire programs are conducted. The risk associated with such testing must be recognized and controlled. A conscious effort must be made to cost effectively moderate the hazards inherent with testing weapons.

Other influences associated with the operation of these facilities are land usage, environmental restrictions, and construction costs. The availability of land for large caliber firing ranges is decreasing. Because of that unavailability, incompatible operations are often conducted contiguously. In these cases, personnel and facilities are subject to high-risk exposures; kickout is one such exposure. Because of the high cost of constructing test facilities, alternatives designed in the context of a risk profile are desirable. Using analytic techniques, like the fault tree analysis contained in this report, such a profile can be developed. This study suggests a profile from which can be derived safe and cost effective alternatives.

b. Specific. This study deals with the problem of kickout, which affects the design of magazines, barricades, and other suppressive structures. Kickout is defined as the escape from a containment structure (such as a test facility) of an unexploded round of ammunition following an explosion in the structure. This study does not present a direct solution to the kickout problem simply because there isn't one. There is no guarantee that an explosion will never happen in a test structure or a round of ammunition will never be ejected. What this study does is define the mechanisms which cause a kickout and logically describe the order of their occurrence. The solution provided in this report is an identification of the events and hazards associated with the kickout phenomenon so the risk can be understood. By controlling selected hazards, the risk is reduced. If it has been reduced to an acceptable degree, the requirements applied to the design and subsequent operation of any facility can be relaxed.

1.2 OBJECTIVES

The objectives of this study are to:

a. Define kickout.

b. Define the mechanisms that cause a kickout.

c. Determine the logical sequence of those mechanisms.

1.3 SUMMARY OF PROCEDURES

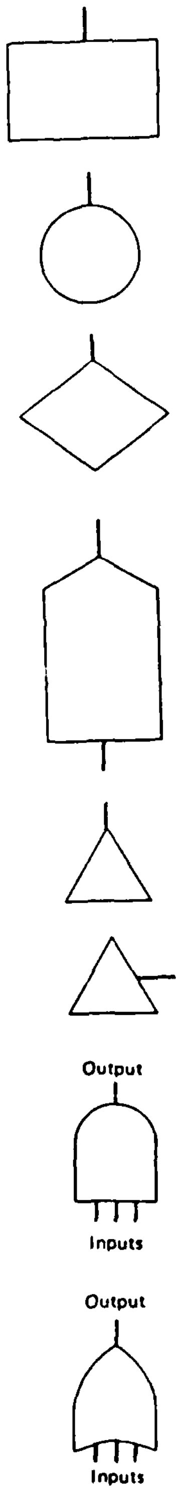
Initially, the main thrust of the investigation was directed towards a literature search. The intent of the search was to identify the available data and to better describe the kickout problem. As the literature search progressed, it became evident the study had to include a foundation - the causes of a kickout. The scope of the project was expanded to include the relationships between those causes and the mechanisms that controlled them. It was natural then to use a Fault Tree Analysis to better understand those mechanisms. An additional benefit of this type of analysis is the use of Boolean Algebra to quantify the results. The results of this study would not only benefit the construction of the new vibration facility but also the construction of new firing barricades at the Main Front firing positions at APG. Many of these facilities are in the vicinity of incompatible operations. Because of this incompatibility the local work force and those who are not related to the test operations are at risk. Information from the literature search and from discussions with personnel at USABRL was incorporated in the design of the fault tree. Once the tree was developed, a computer model was used to identify single point failures and minimal cut sets, the definitions of which are in Appendix B, section 2 of this report. The fault tree and results of the computer model assessment are included in paragraph 1.4. An example model is contained in Appendix C, section 2. A discussion of these results follows in paragraph 1.5.

1.4 SUMMARY OF RESULTS

a. Figures 1.4-1 through 1.4-22 contain an explanation of fault tree symbols followed by the tree.

b. Figures 1.4-23 through 1.4-28 contain the results of the computer model assessment.

1.4 (Cont'd)



The rectangle identifies an event that results from the combination of fault events through the input logic gate.

The circle describes a basic fault event that requires no further development.

The diamond describes a fault event that is considered basic in a given Fault Tree. The possible causes of the event are not developed further, either because the event is of insufficient consequence or the necessary information is unavailable.

The house indicates an event that is normally expected to occur, such as a phase change in a dynamic system.

The triangles are used as transfer symbols. A line from the apex indicates a *transfer in*, and a line from the side shows a *transfer out*.

AND GATE describes the logical operation where all the inputs must occur to produce the output event.

OR GATE describes the logical operation where any one of the inputs will cause the output event.

Figure 1.4-1. Fault tree symbols.

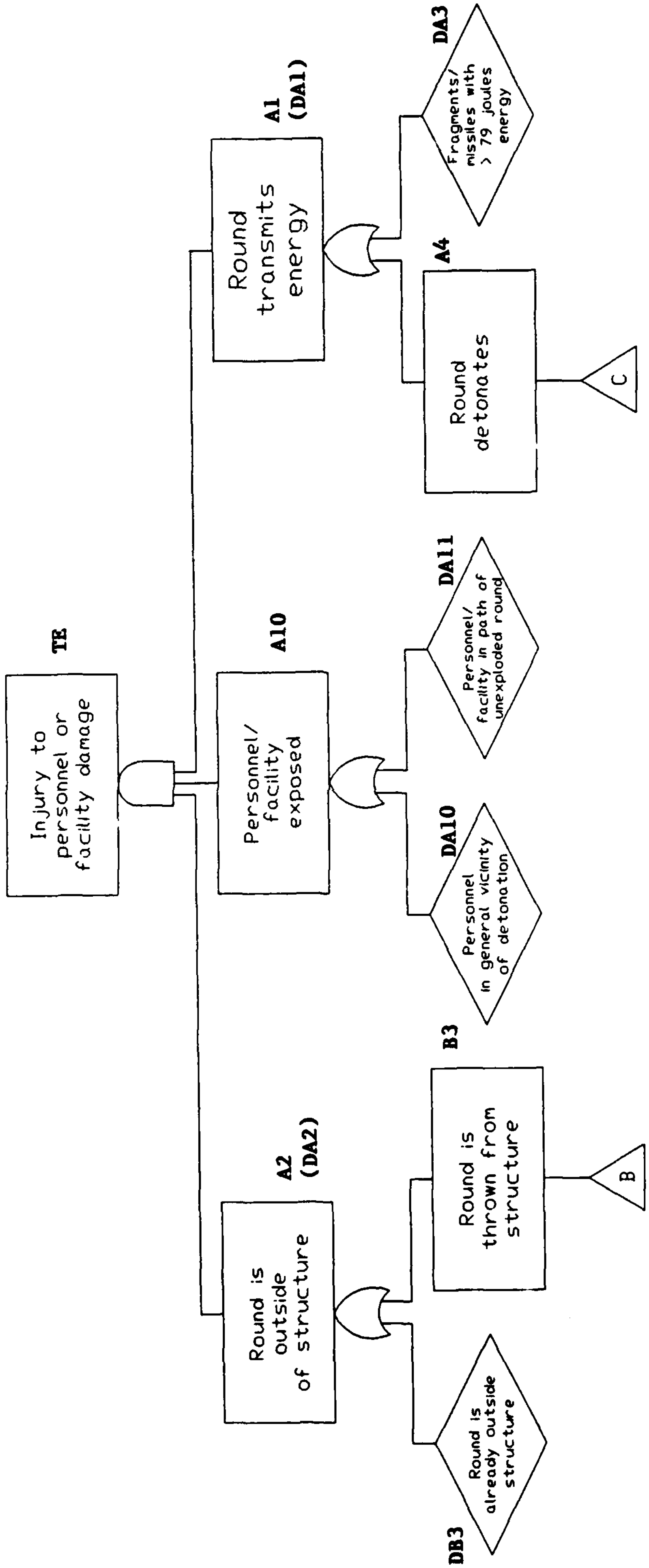
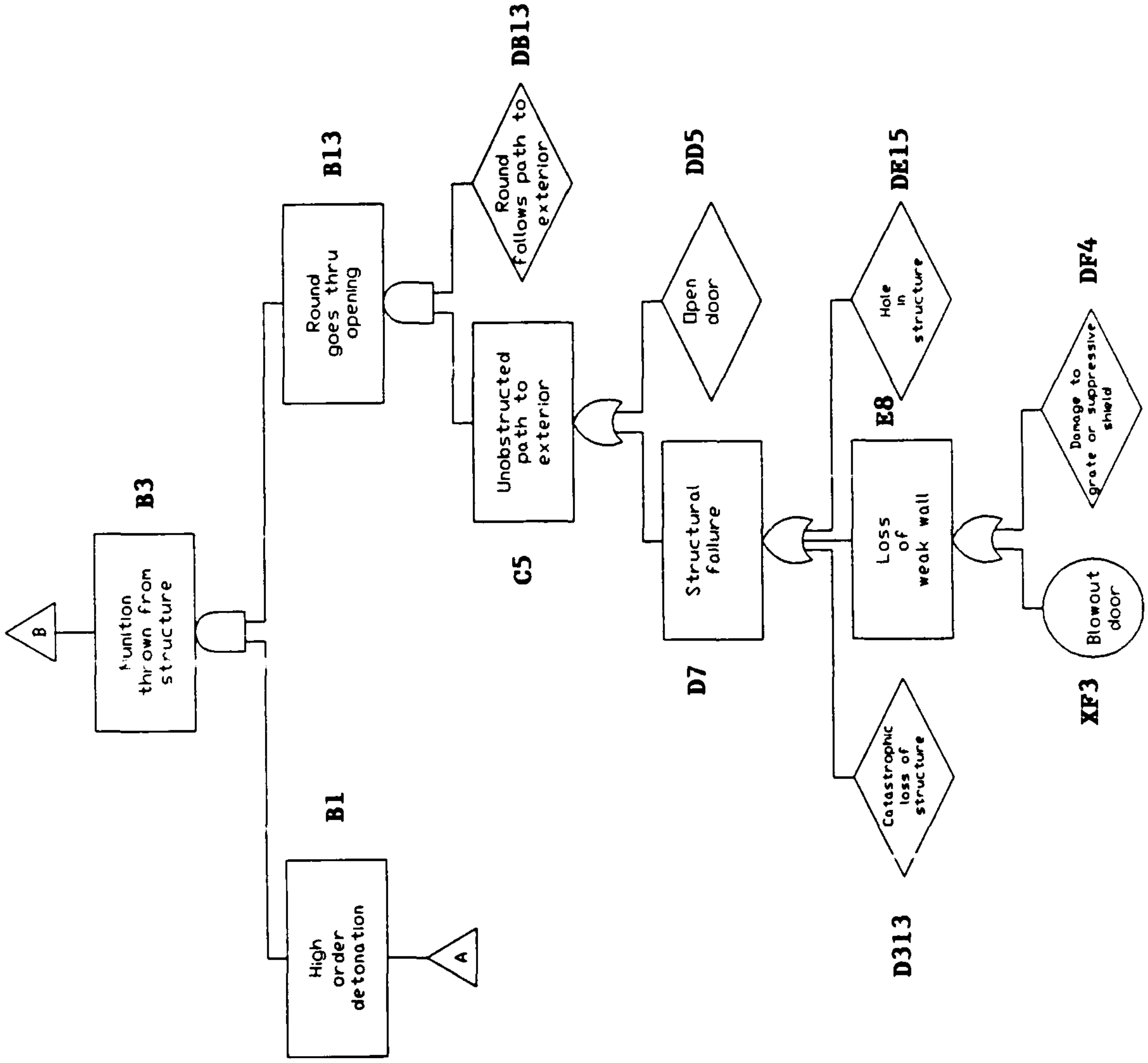

TE
Injury to personnel or facility damage
A1 (DA1)
Round transmits energy
DA3
Fragments/ missiles with > 79 joules energy
A4
Round detonates
C
A10
Personnel/ facility exposed
DA11
Personnel/ facility in path of unexploded round
DA10
Personnel in general vicinity of detonation
A2 (DA2)
Round is outside of structure
B3
Round is thrown from structure
B
DB3
Round is already outside structure

Figure 1.4-2.

1.4 (Cont'd)



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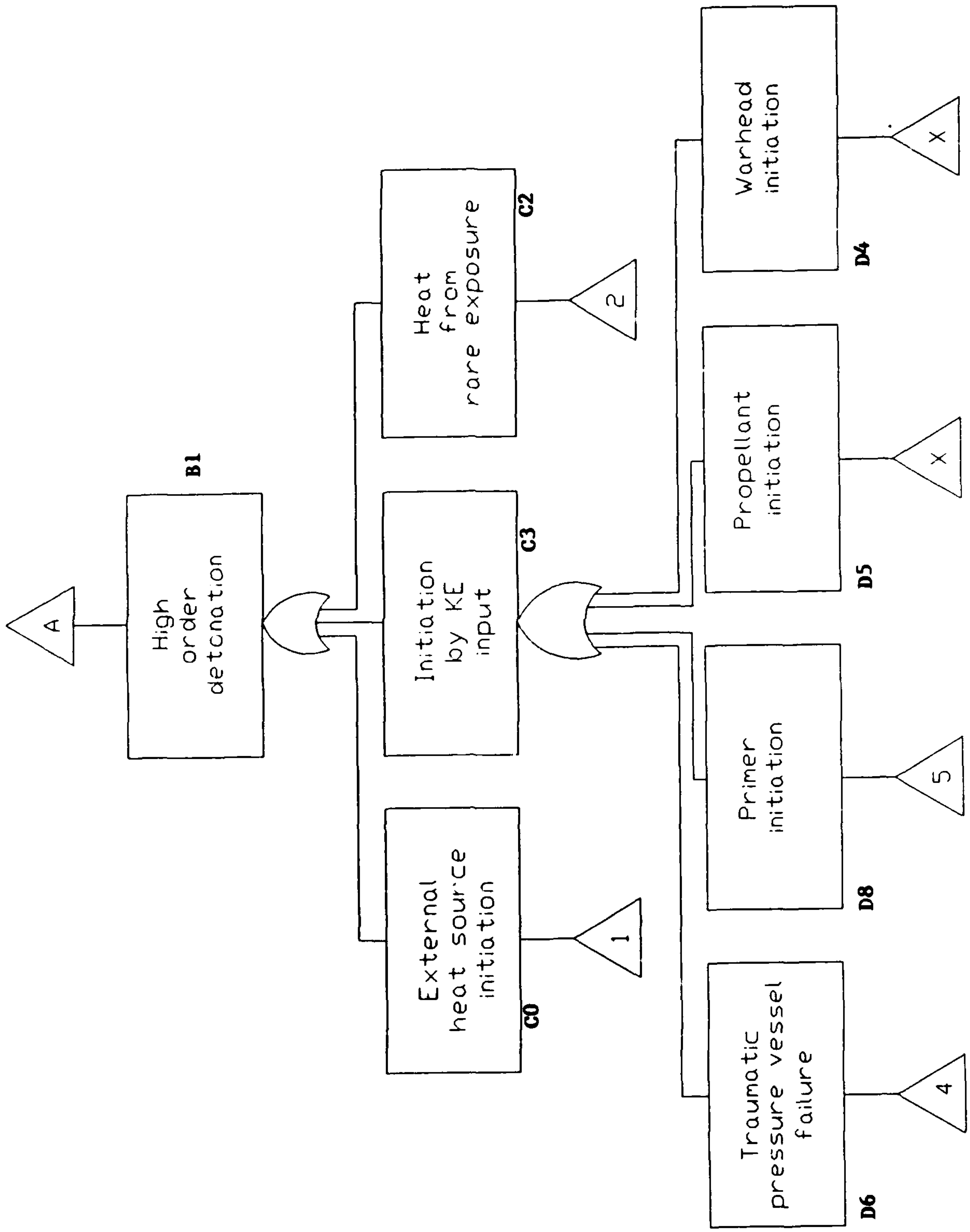

Figure 1.4-4.

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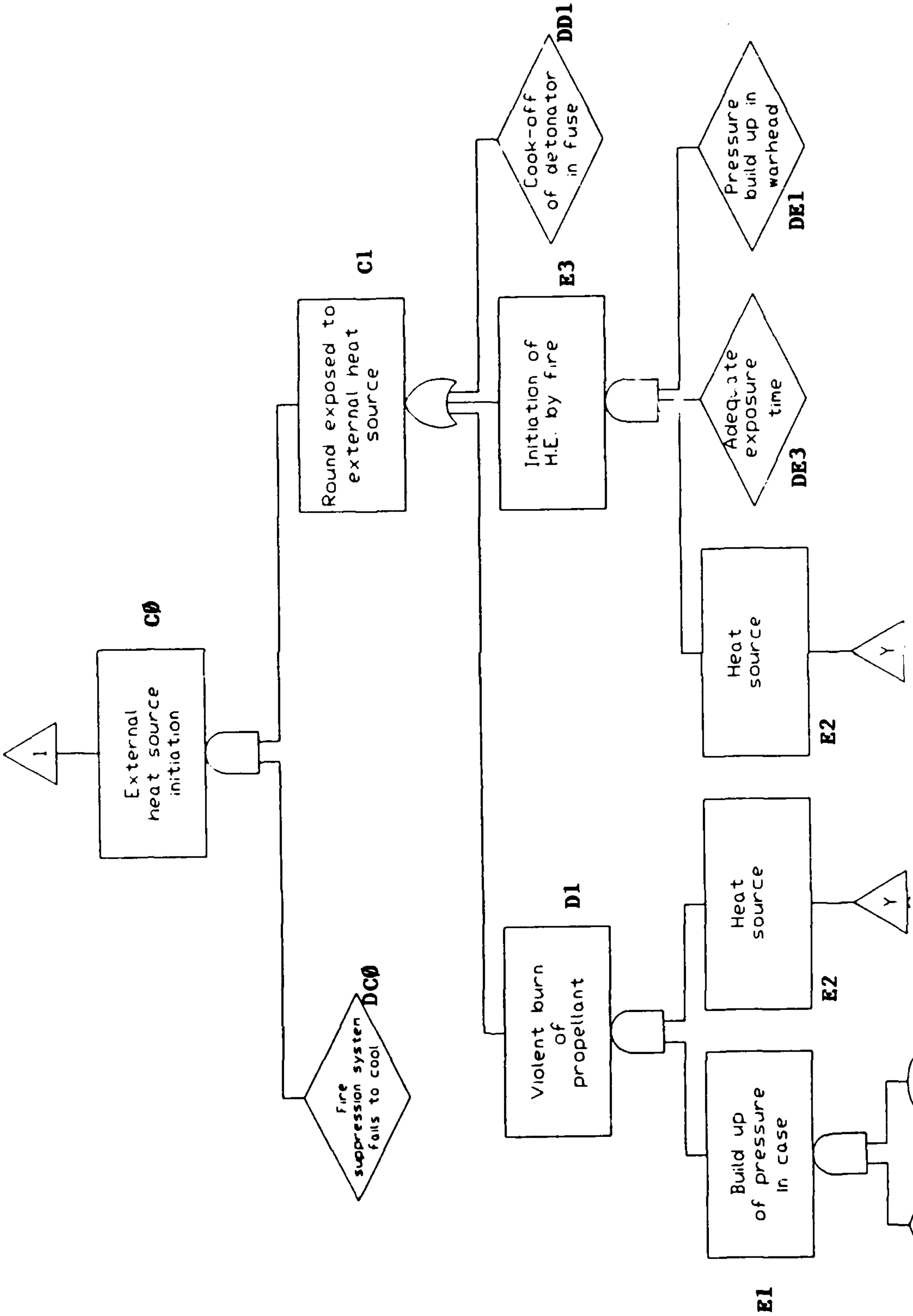

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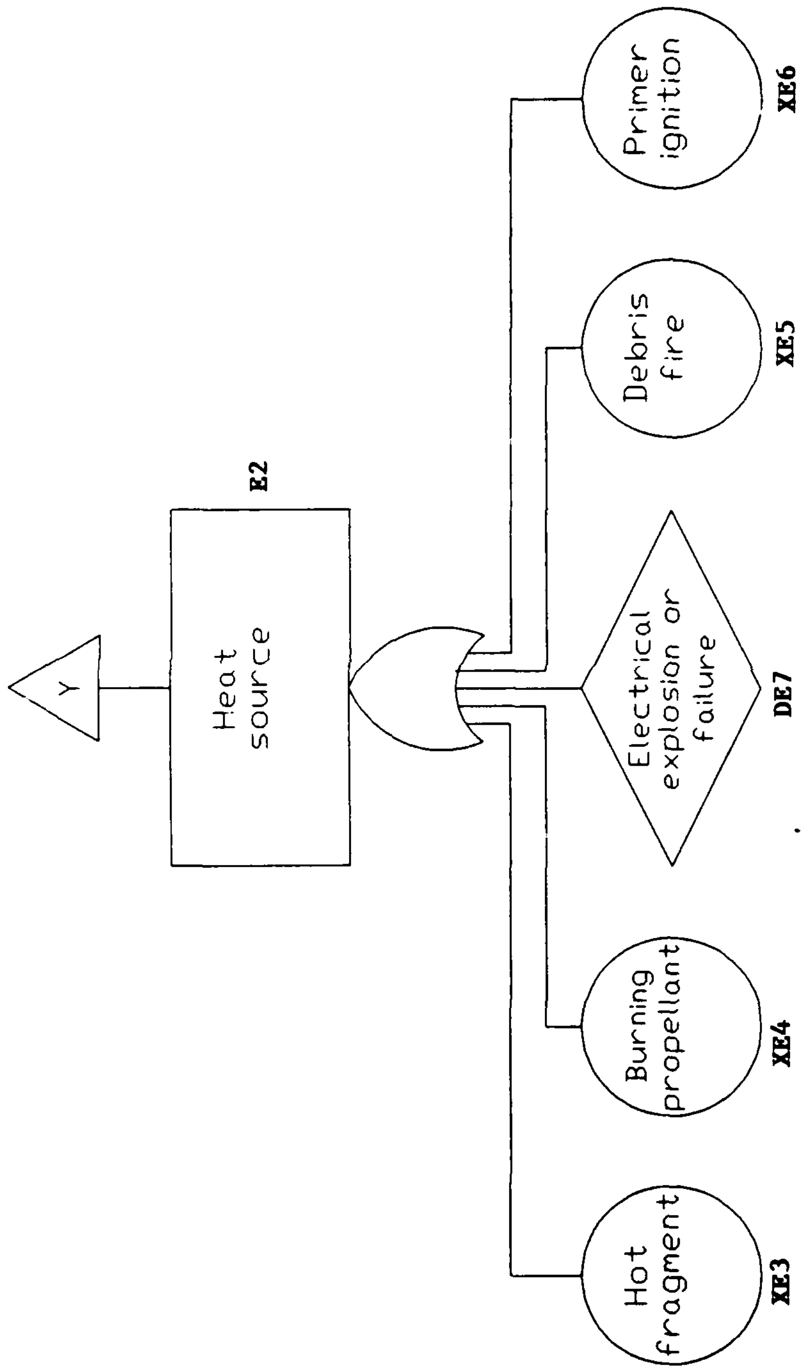

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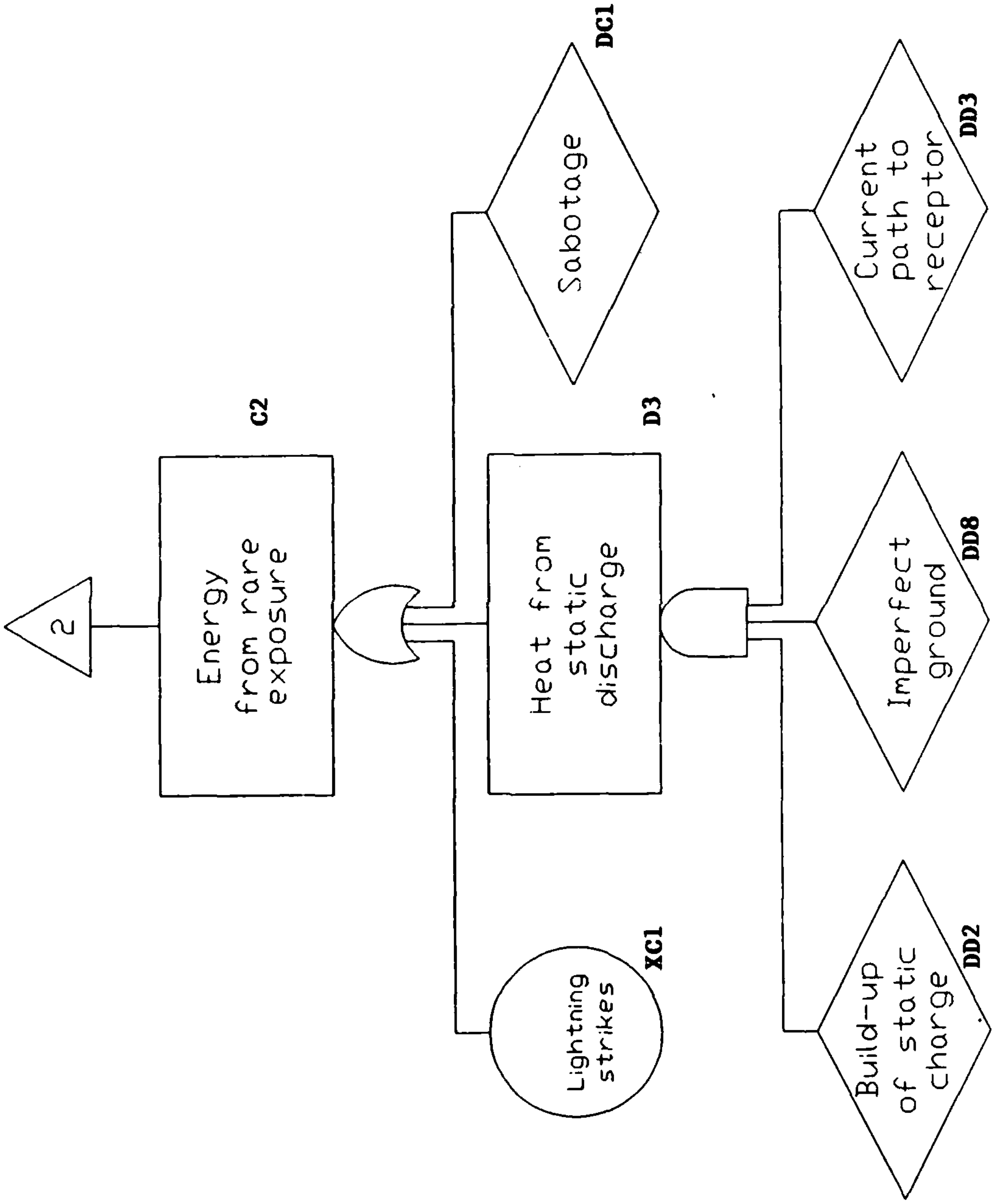

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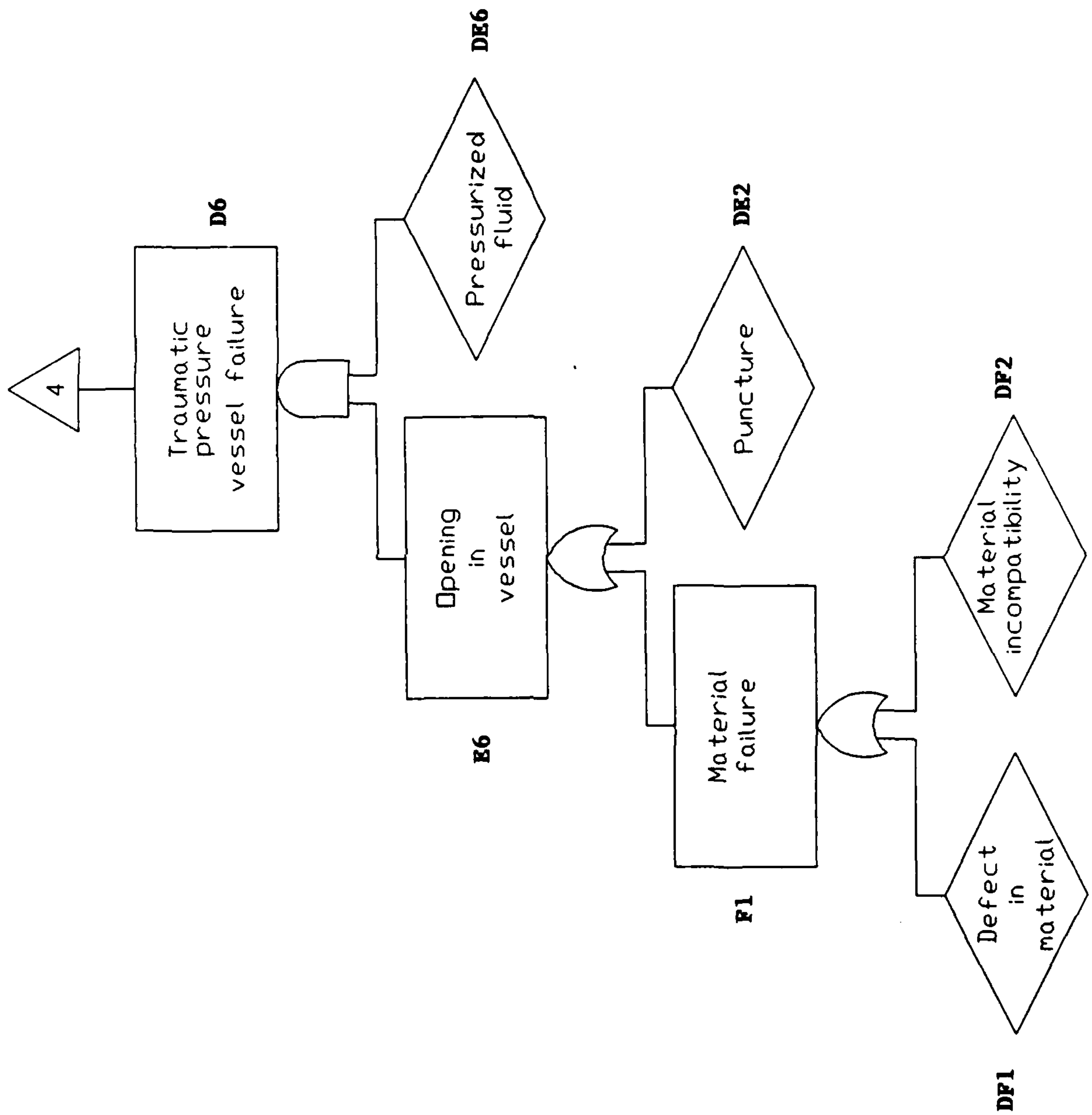

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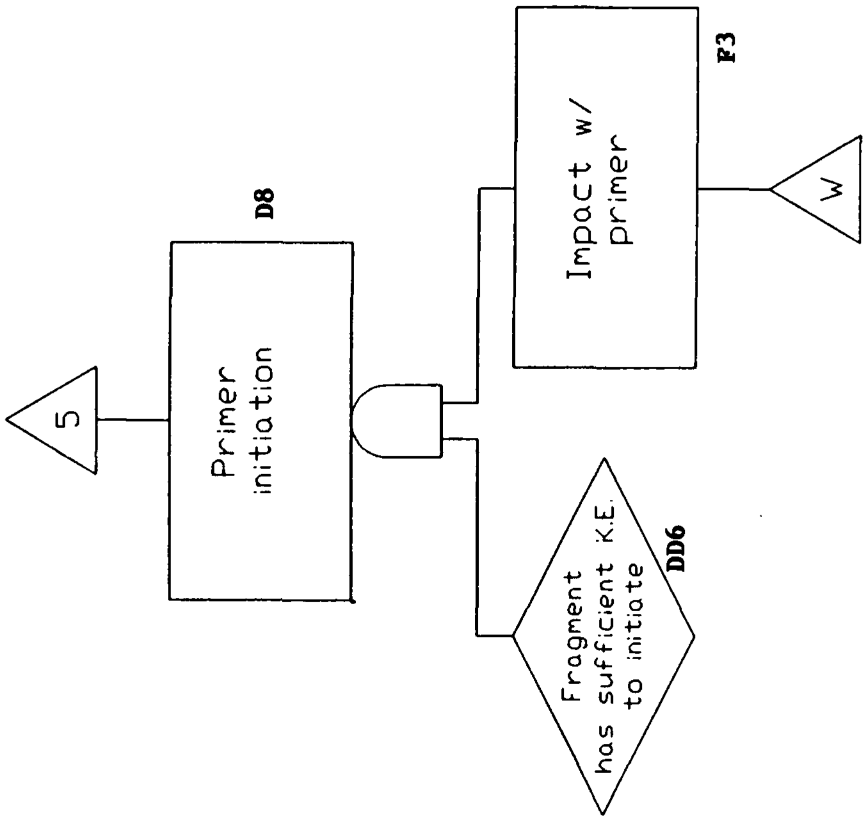

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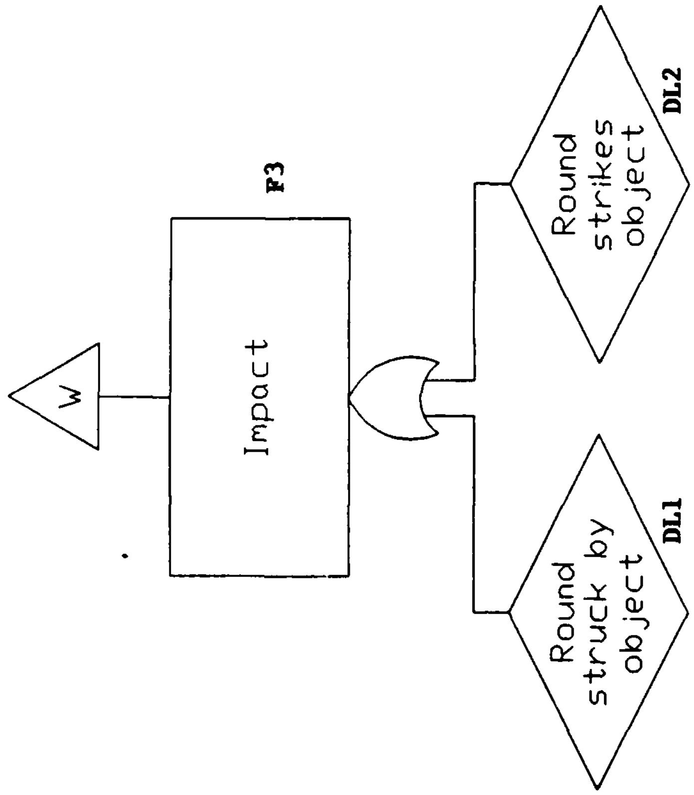
1.4 (Cont'd)



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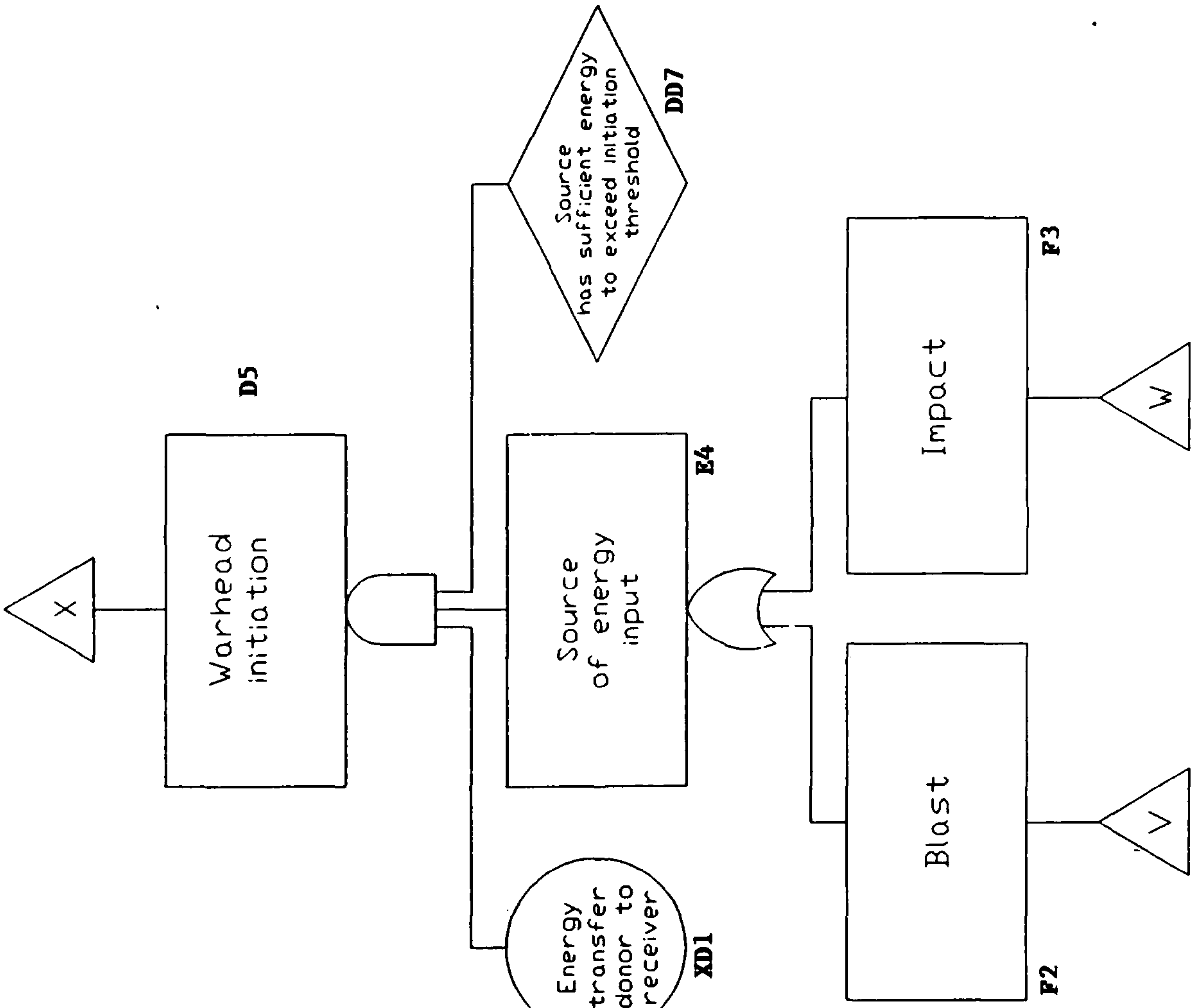

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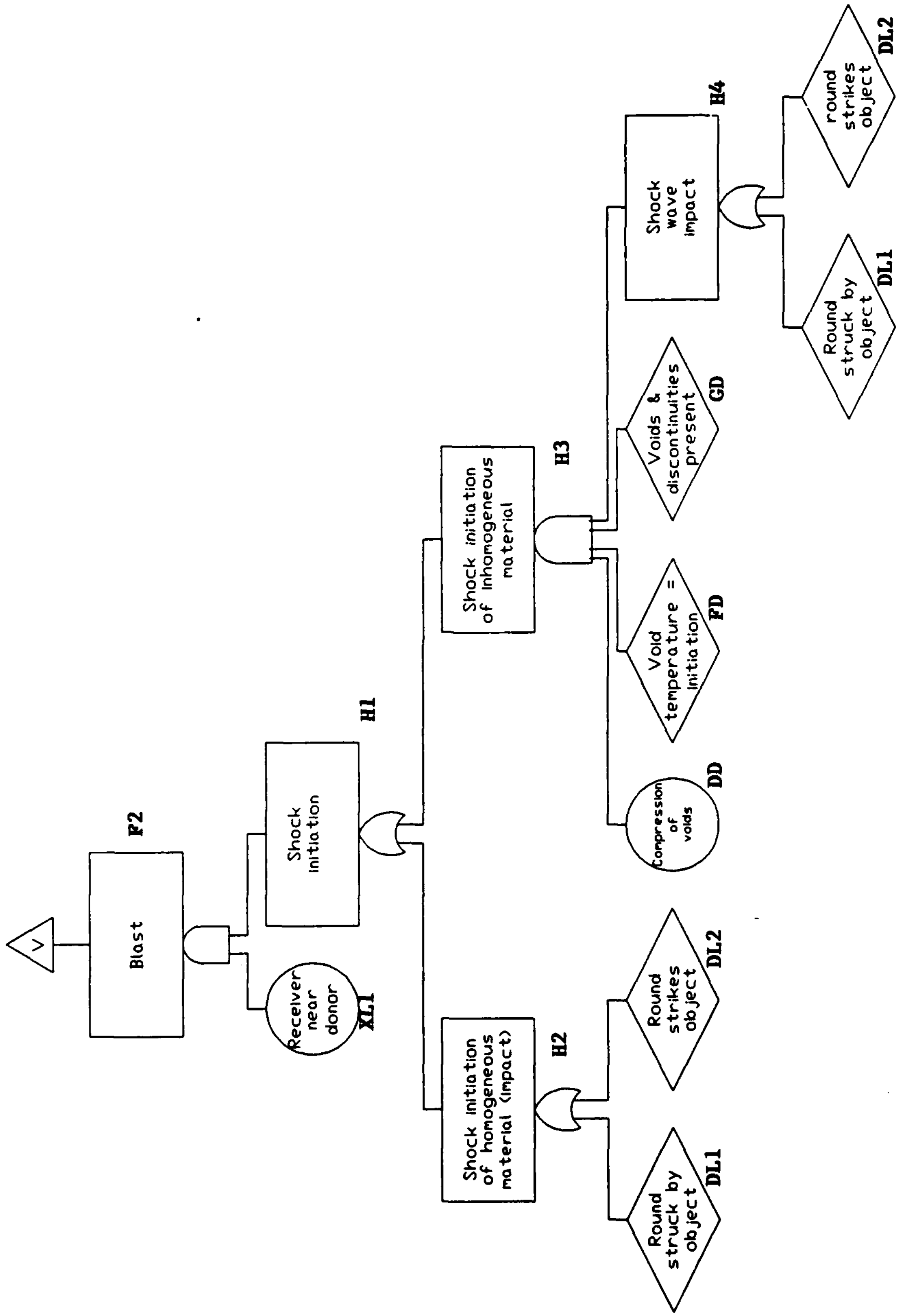

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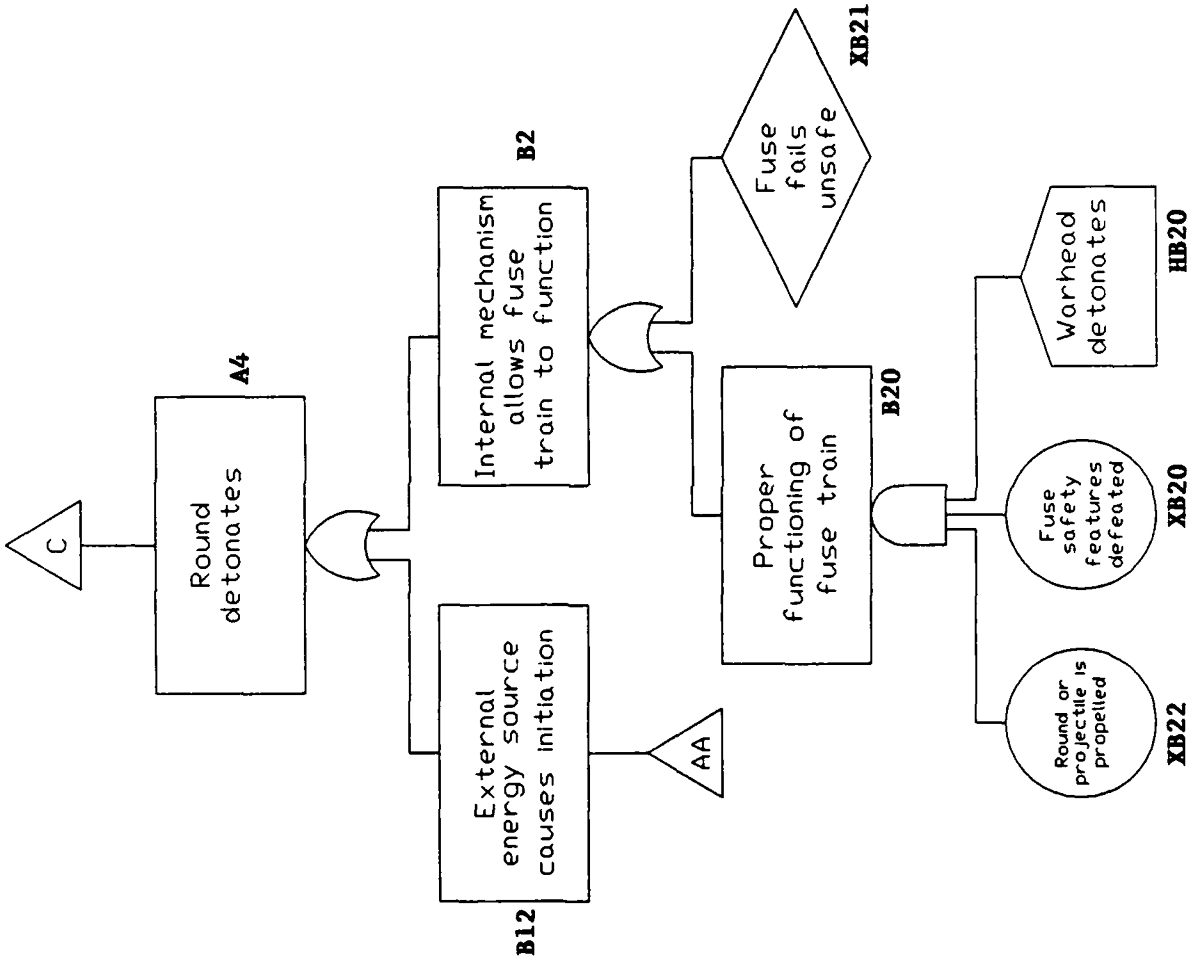
1.4 (Cont'd)



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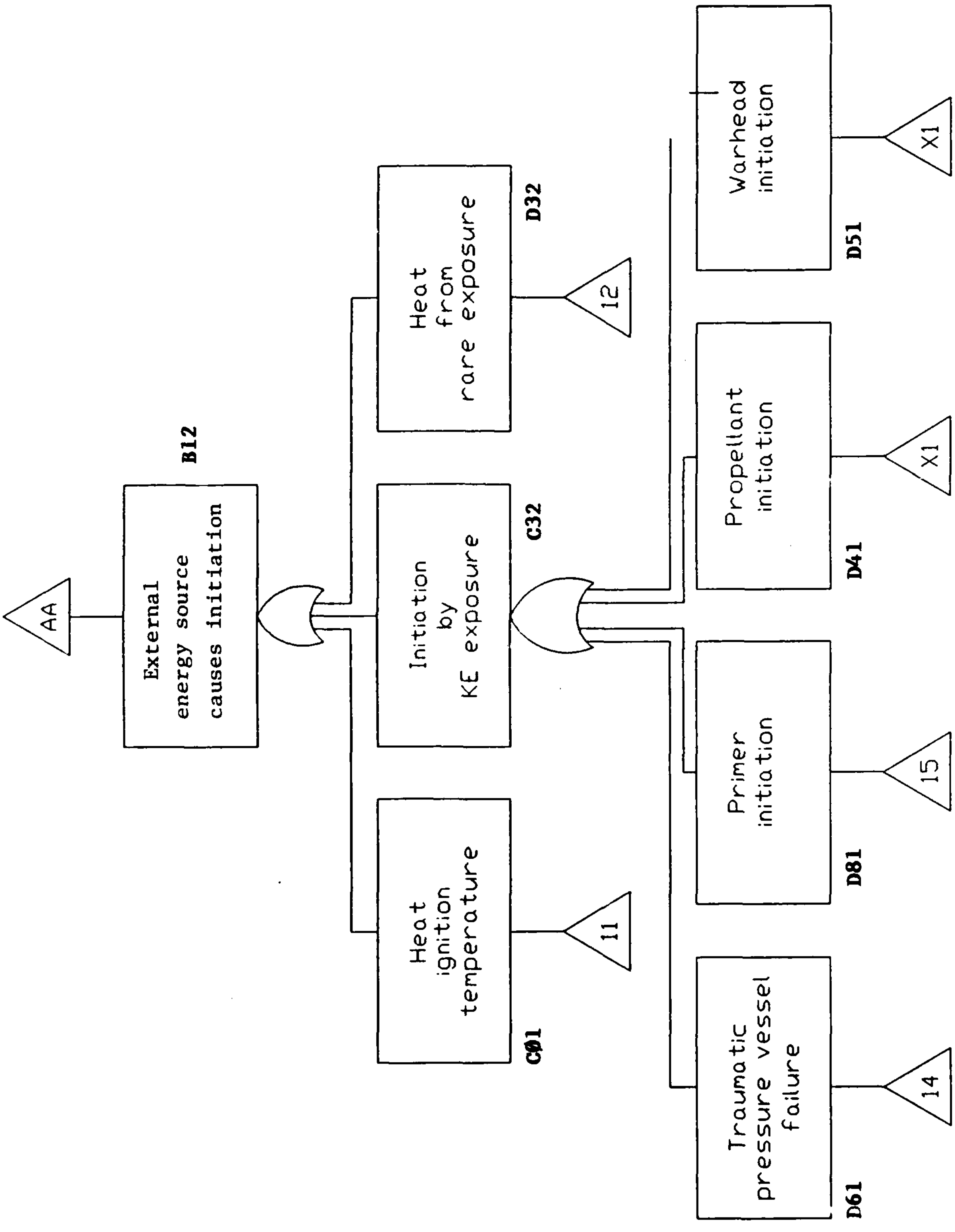

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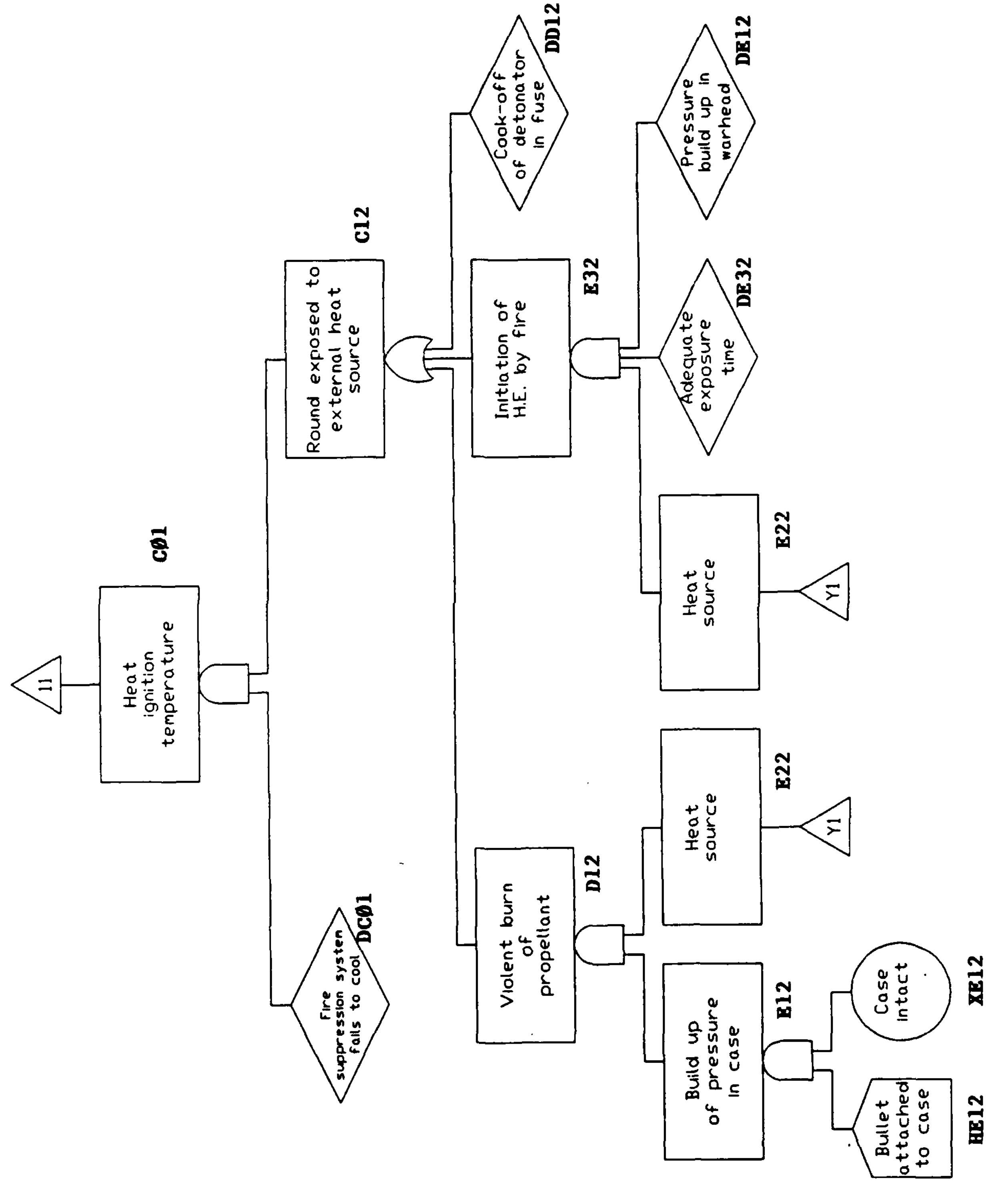
1.4 (Cont'd)



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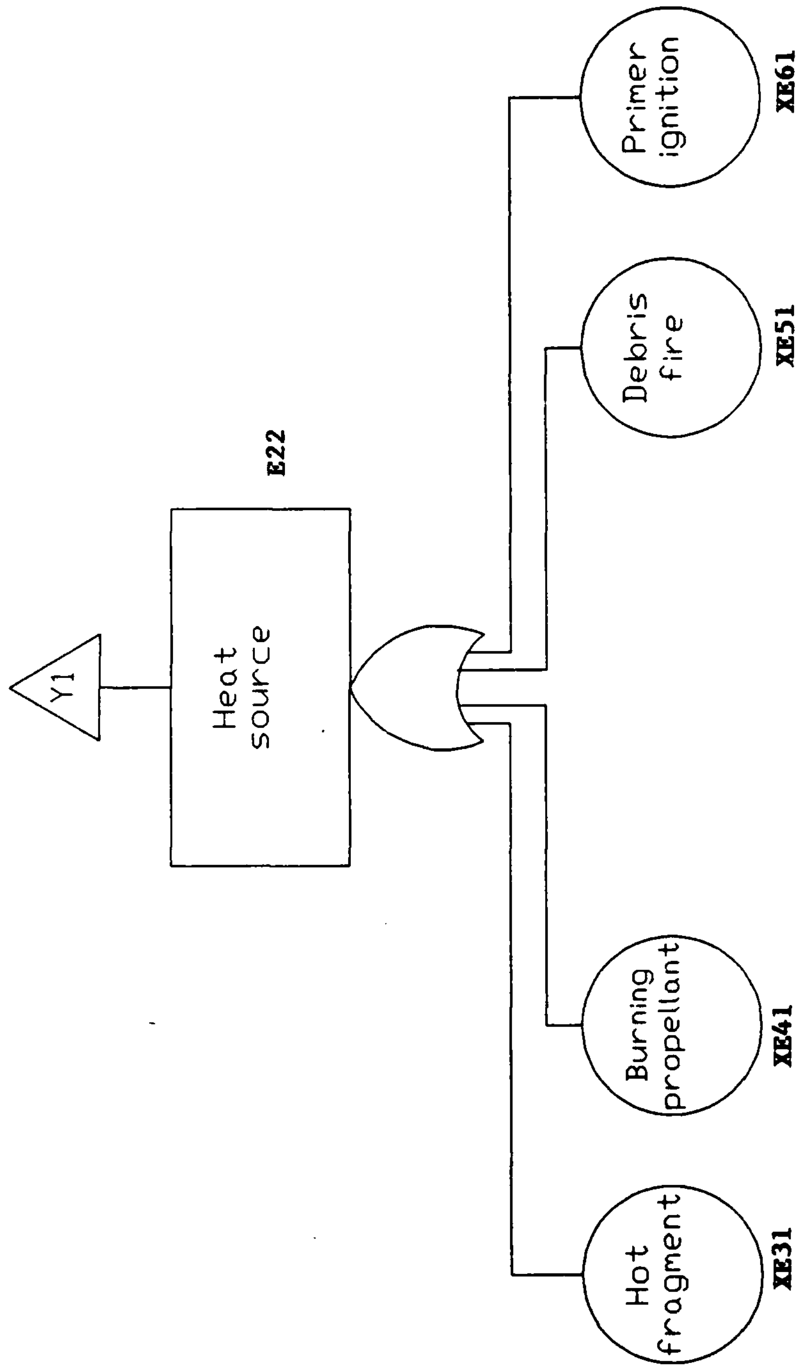

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1.4 (Cont'd)

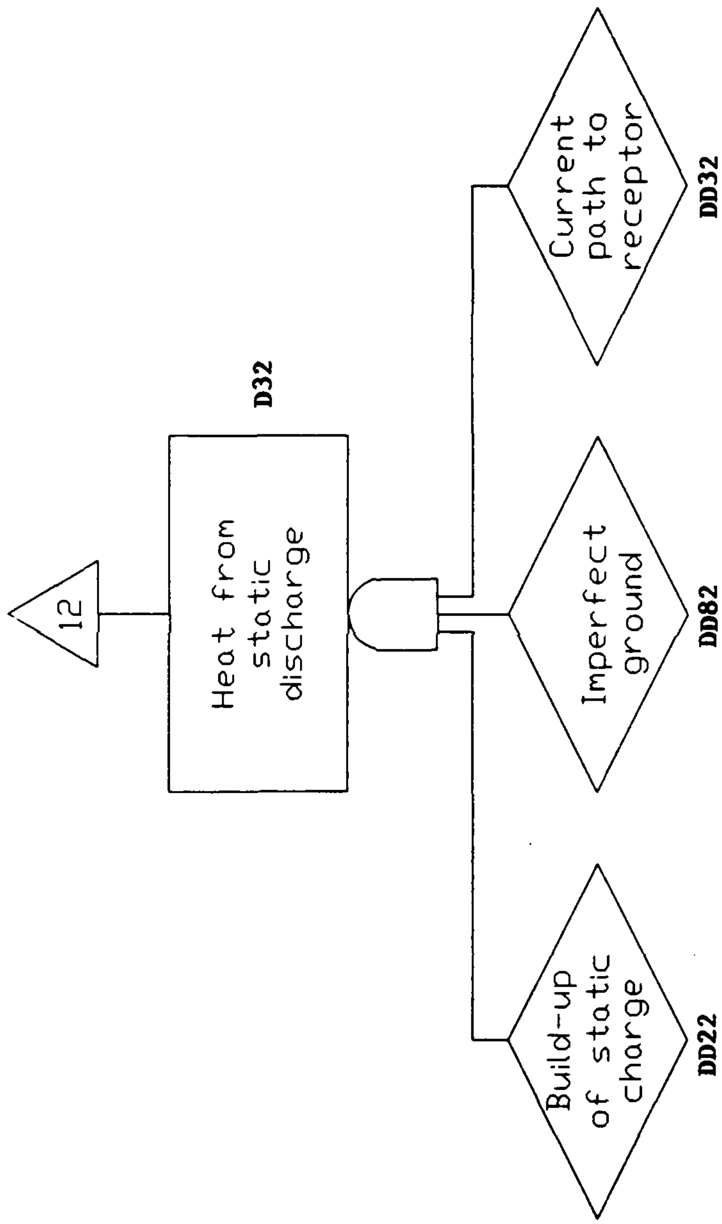


Figure 1.4-17.

1.4 (Cont'd)

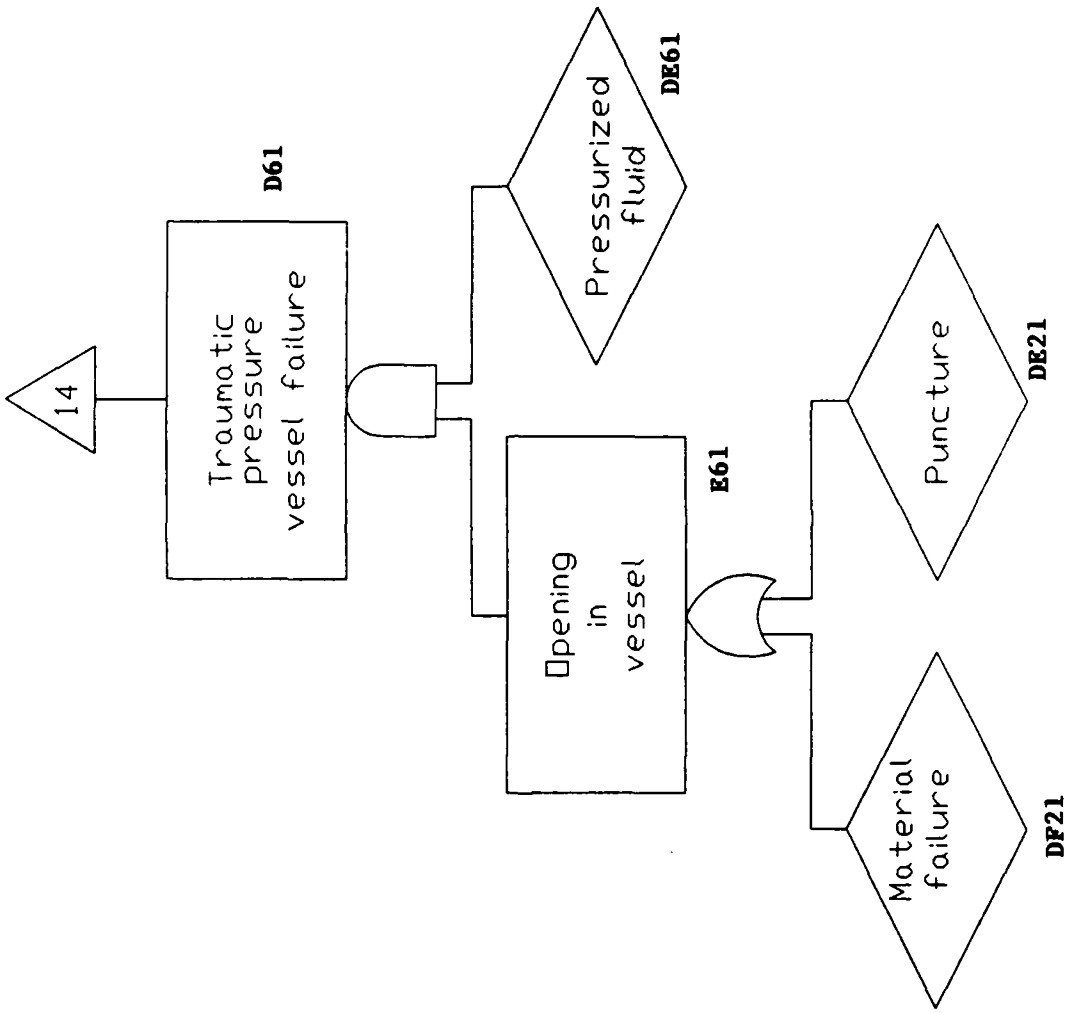
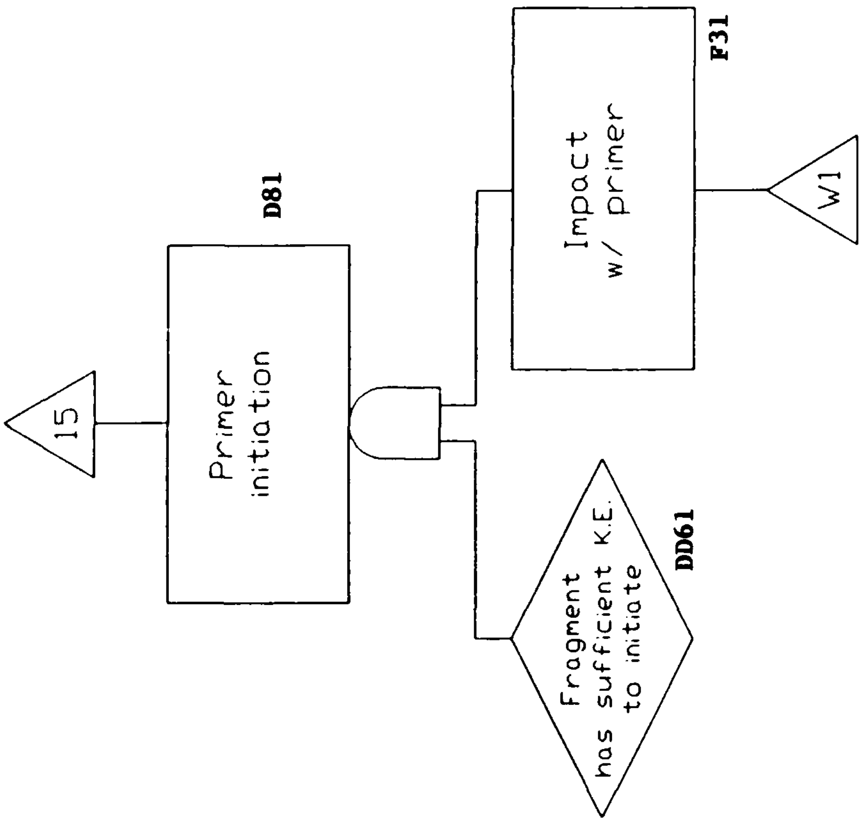


Figure 1.4-18.

1.4 (Cont'd)



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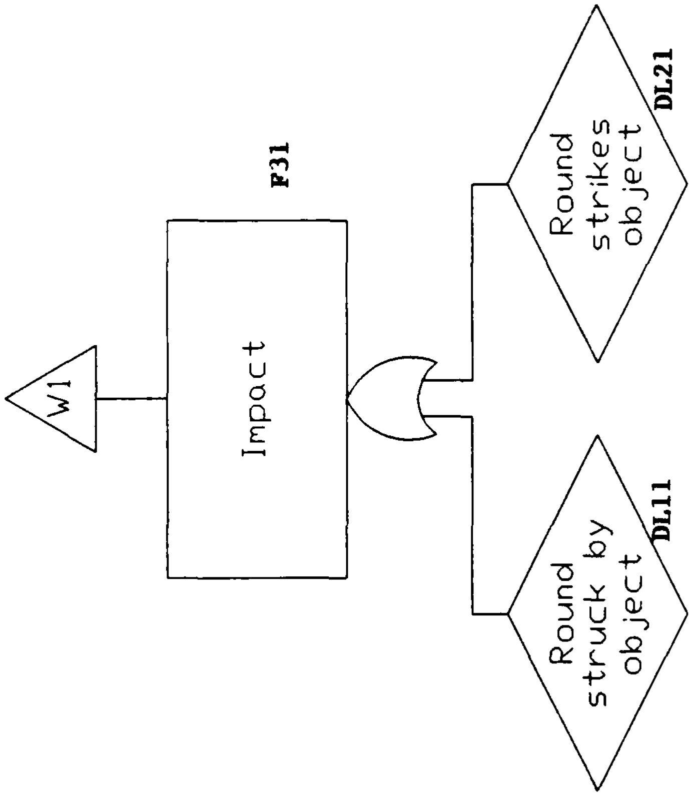
1.4 (Cont'd)



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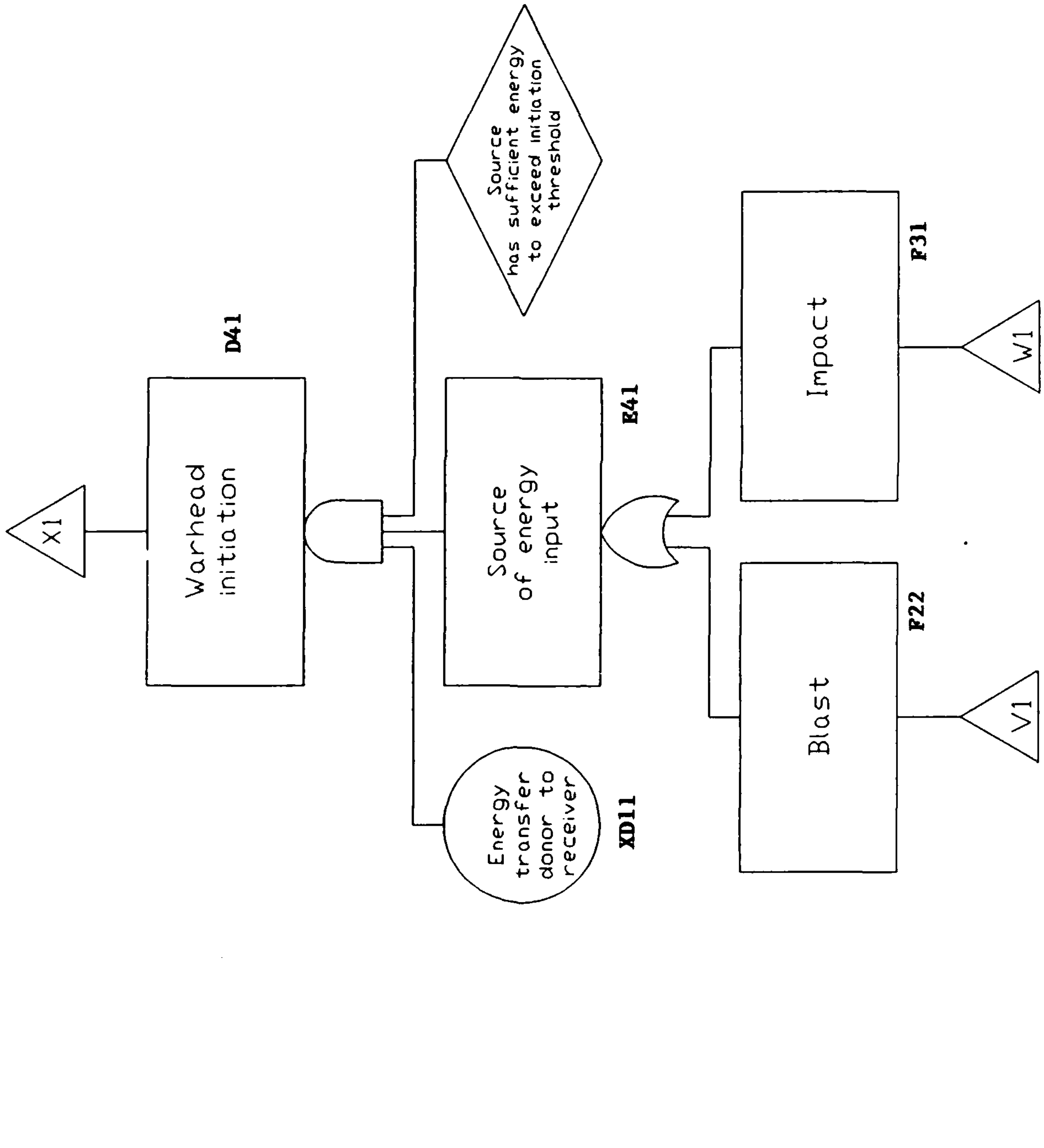

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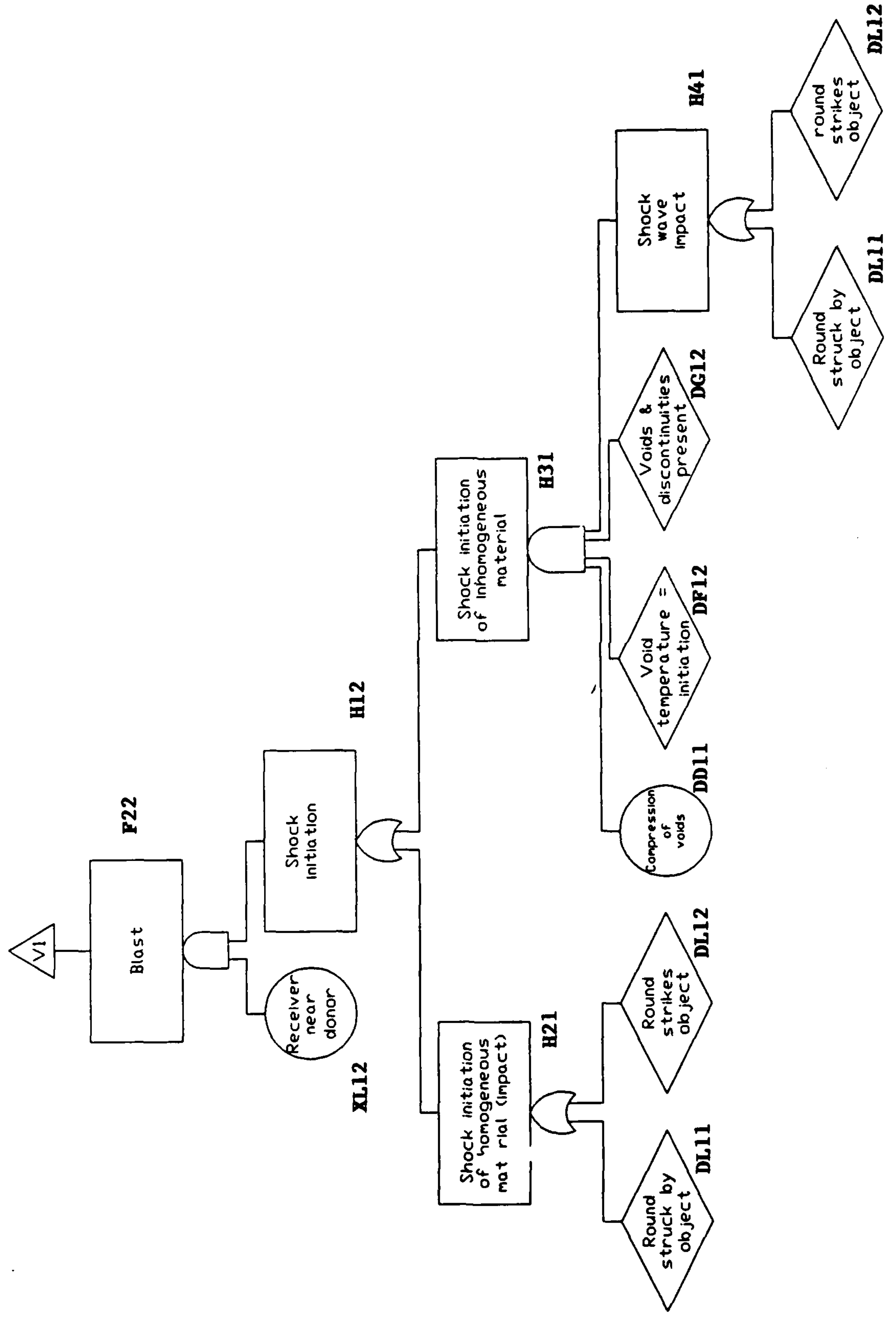

Figure 1.4-22.

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*************************************

 FAULT TREE ANALYSIS PROGRAM

*************************************

INPUT DATA LIST

TOP EVENT : MUNITION OUTSIDE STRUCTURE

GATE DATA
 1   B3 A 2 0 B1 B13 -- -- -- --       MUNITION THROWN FROM STRUCTURE
 2   B1 O 3 0 C0 C2 C3 -- -- --        HIGH ORDER DETONATION
 3   C2 O 1 2 D3 XC1 DC1 -- -- --      HEAT FROM RARE EXPOSURE
 4   C3 O 4 0 D4 D5 D8 D6 -- --        INITIATION BY KE
 5   C5 O 1 1 D7 DD5 -- -- -- --       UNOBSTRUCTED PATH TO EXTERIOR
 6   D1 A 2 0 E1 E2 -- -- -- --        VIOLENT BURN OF PROPELLENT
 7   D3 A 0 3 DD2 DD3 DD8 -- -- --     HEAT FROM STATIC DISCHARGE
 8   D4 A 1 2 E4 XD1 DD7 -- -- --      WARHEAD INITIATION
 9   D5 A 1 2 E4 XD1 DD7 -- -- --      PROPELLENT INITIATION
10   D6 A 1 1 E6 DE6 -- -- -- --       TRAUMATIC PRESSURE VESSEL FAILURE
11   D7 O 1 2 E8 DE13 DE15 -- -- --    STRUCTURAL FAILURE
12   E1 A 0 2 HE1 XE1 -- -- -- --      BUILDUP OF PRESSURE IN CASE
13   E2 O 0 5 XE3 XE4 XE5 XE6 DE7 --   HEAT SOURCE
14   E3 A 1 2 E2 DE1 DE3 -- -- --      INITIATION OF HE BY FIRE
15   E4 O 2 0 F2 F3 -- -- -- --        SOURCE OF ENERGY INPUT
16   E6 O 1 1 F1 DE2 -- -- -- --       OPENING IN VESSEL
17   E8 O 0 2 XF3 DF4 -- -- -- --      LOSS OF WEAK WALL
18   F1 O 0 3 DF1 DF2 DF3 -- -- --     MATERIAL FAILURE
19   F2 A 1 1 H1 XL1 -- -- -- --       BLAST
20   F3 O 0 2 DL1 DL2 -- -- -- --      IMPACT
21   H1 O 2 0 H2 H3 -- -- -- --        SHOCK INITIATION
22   H2 O 0 2 DL1 DL2 -- -- -- --      INITIATION OF HOMOGENEOUS MATERIAL
23   H3 A 1 3 H4 D F G -- --           INIT. OF NON-HOMOGENEOUS MATERIAL
24   H4 O 0 2 DL1 DL2 -- -- -- --      SHOCK WAVE IMPACT
25   D8 A 1 1 F3 DD6 -- -- -- --       PRIMER INITIATION
26   C0 A 1 1 C1 DC0 -- -- -- --       INITIATION BY EXTERNAL HEAT SOURCE
27   B13 A 1 1 C5 DB13 -- -- -- --     ROUND GOES THROUGH OPENING
28   A2 O 1 1 B3 DB3 -- -- -- --       MUNITION OUTSIDE STRUCTURE
29   C1 O 2 1 D1 E3 DD1 -- -- --       RND EXPOSED TO HEAT SOURCE
30          -- -- -- -- -- -- --

FAULT EVENT DATA
 1   DE15 D HOLE IN STRUCTURE
 2   XC1 F LIGHTNING STRIKES
 3   DC1 D SABOTAGE
 4   DD1 D COOK-OFF OF DETONATOR IN FUZE
 5   DD2 D STATIC BUILD-UP
 6   DD3 D CURRENT PATH TO RECEPTOR
 7   XD1 F ENERGY TRANSFER DONOR TO RECEIVER
 8   DD5 D OPEN DOOR
 9   HE1 H BULLET ATTACHED TO CASE
10   XE1 F CASE INTACT
11   DE1 D PRESSURE BUILD-UP IN WAR HEAD
12   XE3 F HOT FRAGMENT
13   XE4 F BURNING PROPELLENT
14   XE5 F DEBRIS FIRE
15   XE6 F PRIMER IGNITION
16   DF2 D MATERIAL INCOMPATIBLITY
17   DF3 D MATERIEL W/ DESIGN DEFECT
18   DE2 D PUNCTURE
19   XF3 F BLOWOUT DOOR
20   DF1 D DEFECTIVE MATERIAL
21   DD8 D IMPERFECT GROUND
22   DD7 D ENERGY EXCEEDS INITIATION THRESHOLD
23   DD6 D FRAGMENT HAS SUFFICIENT KE TO INITIATE
24   DE3 D ADEQUATE EXPOSURE TIME
25   DE13 D CATASTROPHIC LOSS OF STRUCTURE
26   XL1 F RECEIVER NEAR DONOR
27   DL2 D ROUND STRIKES OBJECT
28   DL1 D ROUND STRUCK BY OBJECT
29   D D COMPRESSION OF VOIDS
30   F D TEMPERATURE AT VOID = IGNITION TEMP.
31   G D VOIDS/DISCONTINUITIES PRESENT
32   DE6 D PRESSURIZED FLUIDS
33   DF4 D DAMAGE TO SUPPRESSIVE SHIELD
34   DC0 D FIRE SUPPRESSION SYSTEM FAILS
35   DB13 D ROUND FOLLOWS PATH TO EXTERIOR
36   DE7 D ELECTRICAL EXPLOSION
37   DB3 D RND ALREADY OUTSIDE STRUCTURE
```

Figure 1.4-23. Fault Tree Analysis Program.

1.4 (Cont'd)

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************************************
 FAULT TREE ANALYSIS PROGRAM
*************************************

MINIMUM CUT SET SIZE =  1
MAXIMUM CUT SET SIZE =  3

CUT SETS FOR MUNITION OUTSIDE STRUCTURE

CUT SET #   1
DB3               RND ALREADY OUTSIDE STRUCTURE

CUT SET #   2
DE15              HOLE IN STRUCTURE
XC1               LIGHTNING STRIKES
DB13              ROUND FOLLOWS PATH TO EXTERIOR

CUT SET #   3
DE15              HOLE IN STRUCTURE
DC1               SABOTAGE
DB13              ROUND FOLLOWS PATH TO EXTERIOR

CUT SET #   4
XC1               LIGHTNING STRIKES
DD5               OPEN DOOR
DB13              ROUND FOLLOWS PATH TO EXTERIOR

CUT SET #   5
XC1               LIGHTNING STRIKES
XF3               BLOWOUT DOOR
DB13              ROUND FOLLOWS PATH TO EXTERIOR

CUT SET #   6
XC1               LIGHTNING STRIKES
DE13              CATASTROPHIC LOSS OF STRUCTURE
DB13              ROUND FOLLOWS PATH TO EXTERIOR

CUT SET #   7
XC1               LIGHTNING STRIKES
DF4               DAMAGE TO SUPPRESSIVE SHIELD
DB13              ROUND FOLLOWS PATH TO EXTERIOR

CUT SET #   8
DC1               SABOTAGE
DD5               OPEN DOOR
DB13              ROUND FOLLOWS PATH TO EXTERIOR

CUT SET #   9
DC1               SABOTAGE
XF3               BLOWOUT DOOR
DB13              ROUND FOLLOWS PATH TO EXTERIOR

CUT SET #  10
DC1               SABOTAGE
DE13              CATASTROPHIC LOSS OF STRUCTURE
DB13              ROUND FOLLOWS PATH TO EXTERIOR

CUT SET #  11
DC1               SABOTAGE
DF4               DAMAGE TO SUPPRESSIVE SHIELD
DB13              ROUND FOLLOWS PATH TO EXTERIOR

*****    END OF CUT SET LIST FOR SIZES 1 THRU  3    *****
```

Figure 1.4-24. Fault Tree Analysis Program.

1.4 (Cont'd)

```
************************************

 FAULT TREE ANALYSIS PROGRAM

*************************************

INPUT DATA LIST

TOP EVENT : ROUND TRANSMITS ENERGY

GATE DATA
 1      A4 O 2 0 B12 B2 -- -- -- --           ROUND DETONATES
 2      B2 O 1 1 B20 XB21 -- -- -- --         INTER. MECH. ALLOWS FUZE TO FUNCTION

 3      B20 A 0 3 XB22 XB20 HB20 -- -- --     PROPER FUNCTIONING OF FUSE TRAIN
 4      B12 O 3 0 C32 C01 D32 -- -- --        EXT. ENERGY SOURCE=>FUNCTIONING FUZE

 5      C32 O 4 0 D61 D81 D41 D51 -- --       HEAT INPUT=>INITIATION
 6      C01 A 1 1 C12 DC01 -- -- -- --        INITIATION BY EXT. HEAT SOURCE
 7      D32 A 0 3 DD22 DD82 DD32 -- -- --     HEAT FROM STATIC DISCHARGE
 8      D61 A 1 1 E61 DE61 -- -- -- --        TRAUMATIC PRESSURE VESSEL FAILURE
 9      E61 O 0 2 DF21 DE21 -- -- -- --       OPENING IN VESSEL
10      C12 O 2 1 D12 E32 DD12 -- -- --       ROUND EXPOSED TO EXT. HEAT SOURCE
11      D12 A 2 0 E12 E22 -- -- -- --         VIOLENT BURN OF PROPELLENT
12      E12 A 0 2 HE12 XE12 -- -- -- --       BUILD UP OF PRESSURE IN CASE
13      E22 O 0 4 XE31 XE41 XE51 XE61 -- --HEAT SOURCE
14      D81 A 1 1 F31 DD61 -- -- -- --        PRIMER INITIATION
15      F31 O 0 2 DL11 DL21 -- -- -- --       IMPACT
16      D41 A 1 2 E41 XD11 DD71 -- -- --      PROPELLENT INITIATION
17      D51 A 1 2 E41 XD11 DD71 -- -- --      WARHEAD INITIATION
18      E41 O 2 0 F31 F22 -- -- -- --         SOURCE OF ENERGY INPUT
19      F22 A 1 1 H12 XL12 -- -- -- --        BLAST
20      H12 O 2 0 H21 H31 -- -- -- --         SHOCK INITIATION
21      H21 O 0 2 DL11 DL21 -- -- -- --       INIT. OF HOMOGENEOUS MATERIAL
22      H31 A 1 3 H41 DD11 DF12 DG12 -- --    INIT. OF NON-HOMOGENEOUS MATERIAL
23      E32 A 1 2 E22 DE32 DE12 -- -- --      INITIATION OF HE BY FIRE
24      H41 O 0 2 DL11 DL21 -- -- -- --       SHOCK WAVE IMPACT
25      A1 O 1 1 A4 DA3 -- -- -- --           ROUND TRANSMITS ENERGY

FAULT EVENT DATA
 1      XB21 F FUZE FAIL UNSAFE
 2      XB22 F ROUND IS PROPELLED
 3      XB20 F FUZE SAFETY DEFEATED
 4      HB20 H WARHEAD DETONATED
 5      DC01 D FIRE SUPP. SYS FAILS
 6      DD22 D STATIC CHARGE BLD-UP
 7      DD82 D IMPERFECT GROUND
 8      DD32 D CURRENT PATH TO RECEPTOR
 9      DE61 D PRESSURIZED FLUID IN VESSEL
10      DF21 D MATERIAL FAILS (VESSEL)
11      DE21 D VESSEL PUNCTURES
12      DD12 D FUZE DETONATOR COOK-OFF
13      HE12 H BULLET ATTACHED TO CASE
14      XE12 F CASE INTACT
15      XE31 F HOT FRAGMENT
16      XE41 F BURNING PROPELLANT
17      XE51 F DEBRIS FIRE
18      XE61 F PRIMER IGNITION
19      DD61 D FRAGMENT KE IGNITE PRIMER
20      XD11 F ENERGY TRANSFER-DONOR/RECEIVER
21      DD71 D SOURCE ENERGY > INITIATION THRESHOLD
22      XL12 F RECEIVER NEAR DONOR
23      DL11 D RND STRUCK BY OBJECT
24      DL21 D RND STRIKES OBJECT
25      DD11 D COMPRESSION OF VOIDS
26      DF12 D VOID TEMP. = INITIATION
27      DG12 D VOIDS PRESENT
28      DE32 D ADEQUATE EXPOSURE TIME
29      DE12 D PRESSURE BUILD-UP IN WARHEAD
30      DA3 D FRAGMENTS WITH=>79 JOULES ENERGY
```

Figure 1.4-25. Fault Tree Analysis Program.

```
************************************

 FAULT TREE ANALYSIS PROGRAM

*************************************

MINIMUM CUT SET SIZE =  1
MAXIMUM CUT SET SIZE =  3

CUT SETS FOR ROUND TRANSMITS ENERGY

CUT SET #   1
XB21            FUZE FAIL UNSAFE

CUT SET #   2
DA3             FRAGMENTS WITH=>79 JOULES ENERGY

CUT SET #   3
DC01            FIRE SUPP. SYS FAILS
DD12            FUZE DETONATOR COOK-OFF

CUT SET #   4
DE61            PRESSURIZED FLUID IN VESSEL
DF21            MATERIAL FAILS (VESSEL)

CUT SET #   5
DE61            PRESSURIZED FLUID IN VESSEL
DE21            VESSEL PUNCTURES

CUT SET #   6
DD61            FRAGMENT KE IGNITE PRIMER
DL11            RND STRUCK BY OBJECT

CUT SET #   7
DD61            FRAGMENT KE IGNITE PRIMER
DL21            RND STRIKES OBJECT

CUT SET #   8
XB22            ROUND IS PROPELLED
XB20            FUZE SAFETY DEFEATED
HB20            WARHEAD DETONATED

CUT SET #   9
DD22            STATIC CHARGE BLD-UP
DD82            IMPERFECT GROUND
DD32            CURRENT PATH TO RECEPTOR

CUT SET #  10
XD11            ENERGY TRANSFER-DONOR/RECEIVER
DD71            SOURCE ENERGY > INITIATION THRESHOLD
DL11            RND STRUCK BY OBJECT

CUT SET #  11
XD11            ENERGY TRANSFER-DONOR/RECEIVER
DD71            SOURCE ENERGY > INITIATION THRESHOLD
DL21            RND STRIKES OBJECT

*****   END OF CUT SET LIST FOR SIZES 1 THRU  3    *****
```

Figure 1.4-26. Fault Tree Analysis Program.

```
************************************
 FAULT TREE ANALYSIS PROGRAM
*************************************
INPUT DATA LIST

TOP EVENT : INJ. TO PSNL/FCLTY DAMAGE

GATE DATA
 1        TE A 1 2 A10 DA1 DA2 -- -- --
 2        A10 O 0 2 DA10 DA11 -- -- -- --     PSNL/FCLTY EXPOSURE

FAULT EVENT DATA
 1        DA1 D RND TRNSMTS ENERGY
 2        DA2 D RND OUTSIDE STRUCTURE
 3        DA10 D PSNL IN AREA OF XPLSN
 4        DA11 D PSNL IN PATH OF FRGMNT
```

Figure 1.4-27. Fault Tree Analysis Program.

1.4 (Cont'd)

```
************************************

 FAULT TREE ANALYSIS PROGRAM

*************************************

MINIMUM CUT SET SIZE =   1
MAXIMUM CUT SET SIZE =   3

CUT SETS FOR INJ. TO PSNL/FCLTY DAMAGE

CUT SET #   1
DA1             RND TRNSMTS ENERGY
DA2             RND OUTSIDE STRUCTURE
DA10            PSNL IN AREA OF XPLSN

CUT SET #   2
DA1             RND TRNSMTS ENERGY
DA2             RND OUTSIDE STRUCTURE
DA11            PSNL IN PATH OF FRGMNT

*****   END OF CUT SET LIST FOR SIZES 1 THRU  3   *****
```

Figure 1.4-28. Fault Tree Analysis Program.

1.5 ANALYSIS

a. Literature Search. As mentioned in paragraph 1.3, a comprehensive literature search was conducted. The search covered all calibers of ammunition from small arms to 175 mm. Included was ammunition for mortars, howitzers, field artillery, tanks, and also missiles. Structure types which were investigated included ammunition storage facilities, climatic and vibration test chambers, and firing barricades for protecting personnel and support equipment. Although covered by standing operating procedures (SOPs), modes of transportation and ammunition handling were included. The literature search covered all environments under which ammunition could be stored, transported, or tested. This information would be used to address safety issues regarding the design and operation of new and existing test facilities for the DoD. Over 500 publications were examined and those pertinent listed in Appendix D. The listing has been divided into two groups. The first group of documents are those used to develop the fault tree. The second group contains information about construction materials and techniques which is indirectly related to this study, but not of use in developing the fault tree. The documents in this group were considered of value for a planned follow-on study.

b. Fault Tree. Following the literature search, a kickout scenario was established and diagramed as a fault tree. The tree is a logic diagram consisting of three sections - called branched - each representing one variable of a mathematical statement. Logically, the head event can occur only if the underlying conditions in each branch have been satisfied. Each of the three branches defines one of the general conditions leading to the undesired outcome. That outcome, called the Head Event[1], is defined as injury to personnel or facility damage caused by a missile or by blast overpressure. The tree flows downward from the head event to the specific root causes. General outcomes at the head of the tree are connected to intermediate and root causes (fault events) by logic gates. The gates depict the logical conditions of union and intersection which are analogous to addition and multiplication. In the text, an additive or union condition is represented by an italized *or*; a multiplicative or intersection condition by an italized *and*.

The Head Event occurring as a result of kickout is a very specific and special case. The conditions for that case are: a round of ammunition outside the structure, *and* a person or facility exposed, *and* that a round of ammunition transmits energy. There are two ways a munition might cause damage. If it is intact, the round can impart energy only if it is thrown or propelled *and* directly strikes a receiver. Alternately, it can detonate. Where the detonation occurs is significant. An exploding bomb can cause damage within some limited radius. If no receiver is within that radius, no damage or injury can be imparted. At military installations, undesirable exposures often exist; people and facilities are usually within the radius at which a bomb, detonating unsuppressed, can cause damage or injury. Explosives are stored in a way that limits this exposure. They are isolated from populated areas *and* stored in bunkers designed to contain or direct the missile and shock wave that might

[1] In this report, the terms "Head Event" and "Top Event" are interchangeable.

1.5 (Cont'd)

result from an explosion. The left branch of the tree details the way blast and fragmentation mitigation features of a protective structure can be defeated. This branch defines the circumstances that must exist for a receiver to be directly exposed to an unexpected energy transfer. Most often, direct exposure occures when ammunition is being packed or unpacked, transported, or handled during testing. While exposure clearly exists in these cases, the risk of an accident is controlled through the use of training and special procedures which minimize the likelihood of an event.

For a kickout to occur, a round of ammunition must be thrown outside a suppressive structure. An impulsive energy source *and* a path out of the structure must be present, *and* the round, when thrown, must travel along that path. An impulsive release of energy is necessary for a kickout to occur. That release might result from a detonation, a pressure vessel failure, or an electrical explosion. A path out of the containment structure might exist because of a structural failure, an inherent weakness, or because a natural opening exists (e.g. doors, windows, or frangible surfaces).

Exposure of personnel and facilities to the hazards of kickout are briefly detailed in the central branch of the tree. The branch is separated into two sections. One is the blast overpressure hazard and the other a missile or fragment hazard. Neither of these conditions have been developed because of their complexity although both normally exist.

The third condition that must be met is defined in the right branch of the tree. For damage to be incurred, the kicked-out munition must transfer energy. The transfer might result from the blast shock of the detonation, *or* from missiles such as secondary fragments. A fragment can only cause damage if it directly strikes a receiver *and* transfers sufficient energy (the accepted lower limit for that energy transfer is 79 joules). Another way for a munition to cause injury or damage is by its detonation. This could be caused by the proper functioning of internal mechanical *or* electrical mechanisms, *or* by the application of heat from an external energy source.

If the probability or occurrence of the undesired event weasel, P, were to be calculated, it would be the product of probabilities of the three directly contributing branches as follows:

$$P = P_{LB} \times P_{CB} \times P_{RB} \qquad (1)$$

where:

- P = the probability of occurrence of the Head Event.
- P_{LB} = the probability a round of ammunition is outside the structure, left branch of the tree.
- P_{CB} = the probability a person or facility is exposed, center branch of the tree.
- P_{RB} = the probability a round of ammunition transmits energy, right branch of the tree.

1.6 CONCLUSIONS

It is concluded that:

a. Because the developed Fault Tree model was more extensive than was anticipated, it was impractical, given the scope of this study, to quantify. Even so, it is clear the possibility of the Head Event occuring does exist, but only if the complex set of conditions defined by the tree have been satisfied.

b. Allocating funds to totally eliminate the possibility of a kickout's occurrence is unnecessary and unreasonable.

c. Elimination of the possibility of the Head Event is impossible. However, along string of events, which is diagramed in each branch of the tree, is required to satisfy that condition. That likelihood can be reduced by selectively manipulating events in that string.

1.7 RECOMMENDATIONS

It is recommended that:

a. Operating restrictions imposed on test facilities be reevaluated in view of the finding of this report.

b. Careful considerations be given to new innovative designs and constructions techniques of protective structures.

c. A second study be conducted to better define the likelihood of occurrence of the Head Event.

APPENDIX A. FAULT TREE DEFINITIONS

1. Cut Set - a combination of fault events whose occurrence as a set will cause the top event.

2. Donor - a round of ammunition which functions in the vicinity of other rounds of ammunition thus imparting energy to them.

3. Event

   a. Refers to the round detonating when regarding ammunition.

   b. Refers to an occurrence in the tree.

4. Gate - connects the events in the fault tree. Gates also determine the mathematical operations using the rules of Boolean Algebra to calculate probabilities. In the text a gate appears as an italicized *and* or an *or*. An *and* represents the logical condition INTERSECTION which is multiplicative; an *or* gate represents the UNION and is additive.

5. Head or Top Event - the main event of the fault tree, the undesired outcome.

6. Kickout - when a round of ammunition which does not detonate from an initial event in a structure is thrown from the structure.

7. Minimal Cut Set - the smallest combination of fault events that causes the Head Event. This gives a qualitative ranking to each fault event on the tree with regard to its contribution to the head event.

8. Receiver - a round of ammunition which receives energy when another round of ammunition in the vicinity functions.

9. Risk - the expected value associated with a given hazard; it is the product of the severity of a hazard and the likelihood of its occurence. Probabilities have not been calculated or assigned to individual events because it is beyond the scope of this report to do so. In this report, risk has several contexts: when pertaining to kickout, it is the consequence caused by a round detonating or escaping a containment structure after an event has occured; when pertaining to a fault tree, it is the head event.

10. Single Point Failure - an individual event on the fault tree that regardless of its position on the tree, will cause the head event to take place.

11. Unrelated - used in reference to people or facilities which are not directly involved in a testing scenario but could be injured or damaged because of their proximity to a test when a kickout occurs.

APPENDIX B. EXAMPLE OF FAULT TREE MODEL, CUT SETS, AND PROBABILITIES

This study would be incomplete without an example demonstrating the value of a fault tree analysis. Using the entire tree from the text of the report would be a cumbersome and tedious adventure. As an illustration of how to interpret a fault tree and how to derive the minimal cut sets, consider the following example. Figure C-1 is based on the fault tree in the text, however, it is terminated at the third level of the tree. This simpler tree has six fault events and three intermediate events leading to the head or top event. At least some of the fault events in the third rank must exist before the top event can occur. This can be shown using the Laws of Boolean Algebra. The following symbols are directly taken from Figure C-1:

$$TE = A1 \textit{ and } A2 \textit{ and } A10 \qquad (2)$$

$$A1 = B1 \textit{ or } B2 \qquad (3)$$

$$A2 = B5 \textit{ or } B6 \qquad (4)$$

$$A10 = B3 \textit{ or } B4 \qquad (5)$$

therefore:

$$TE = A1*A2*A10 \qquad (6)$$

$$= (B1+B2)(A2*A10)$$

$$= B1*A2*A10+B2*A2*A10$$

$$= B1*A10(B5+B6)+B2*A10(B5+B6)$$

$$= B1*A10*B5+B1*A10*B6+B2*A10*B5+B2*B6*A10$$

$$= A10(B1*B5+B1*B6+B2*B5+B2*B6)$$

$$= (B3+B4)(B1*B5+B1*B6+B2*B5+B2*B6)$$

$$= B1*B3*B5+B1*B4*B5+B1*B3*B6+B1*B4*B6 \qquad (7)$$

$$+B2*B3*B5+B2*B3*B6+B2*B4*B5+B2*B4*B6$$

The fully expanded expression has eight terms, each comprised of three fault events. Thus, the fewest number of fault events that must exist for the top event to occur is three. There are eight such triplets. To simplify the mathematical gyrations, a computer algorithm can be used to derive the cut sets. Table C-2 is the software - generated listings of singlets (single point failures), doublets and triplets that represent the minimal cut sets. Note that the computer lists eight triplets which corresponds to those shown in the hand derivation, equation 7, above. The probability of the top events occurring is the sum of the products of the probabilities of the minimal cut sets, bottom of Table C-2, this appendix.

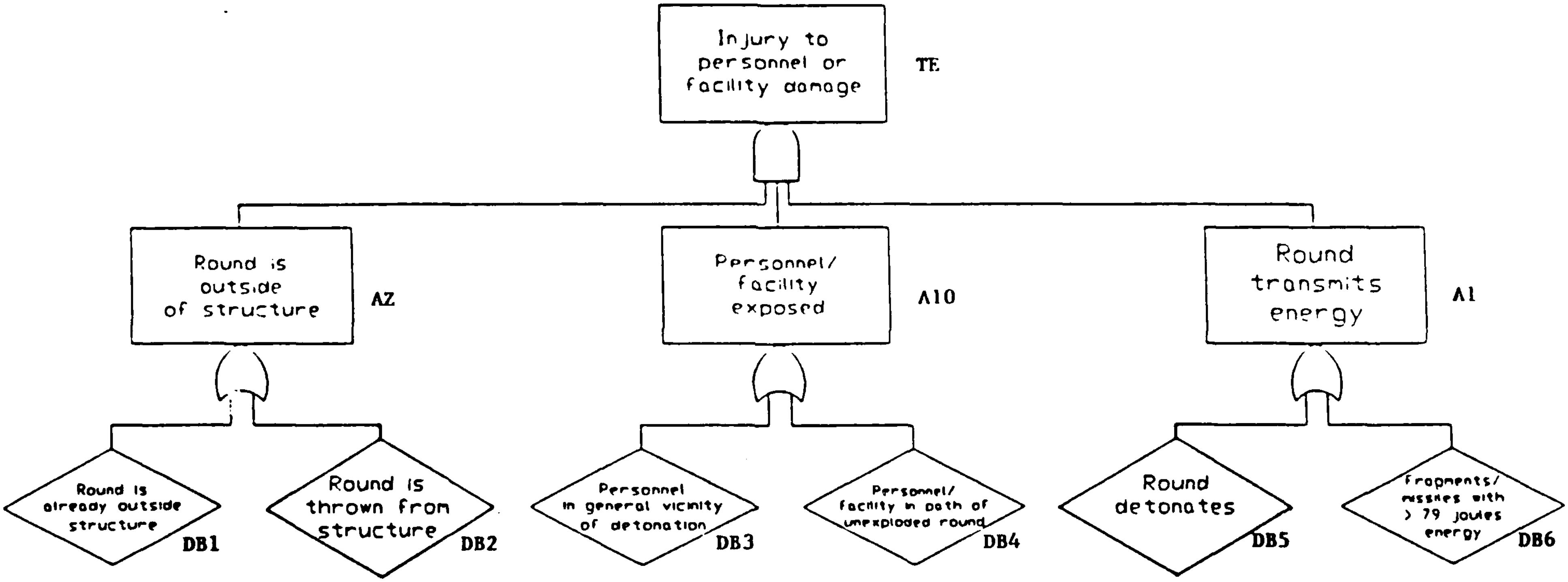

Figure B-1. Example fault tree.

TABLE B-1. EXAMPLE FAULT TREE INPUT DATA LIST

```
************************************

 FAULT TREE ANALYSIS PROGRAM

*************************************

INPUT DATA LIST

TOP EVENT : INJ TO PERSONNEL OR FACILITY DAMAGE

GATE DATA
 1        TE A 3 0 A1 A10 A2 -- -- --
 2        A1 O 0 2 DB1 DB2 -- -- -- --        ROUND IS OUTSIDE OF STRUCTURE
 3        A10 O 0 2 DB3 DB4 -- -- -- --       EXPOSURE
 4        A2 O 0 2 DB5 DB6 -- -- -- --        ROUND TRANSMITS ENERGY
 5            -- -- -- -- -- --

FAULT EVENT DATA
 1        DB1 D RND OUTSIDE STRUCTURE     0.300D-02
 2        DB2 D RND THROWN FM STRUCTURE     0.100D-02
 3        DB3 D PSNL IN VCNTY OF DET.     0.100D-01
 4        DB4 D IN PTH OF FRGMT     0.750D-02
 5        DB5 D RND DET           0.100D-03
 6        DB6 D FRGMT W/  79 JOULES     0.100D-02
```

TABLE B-2. CUT SETS FOR EXAMPLE FAULT TREE

```
**************************************

FAULT TREE ANALYSIS PROGRAM

***************************************

MINIMUM CUT SET SIZE =  1
MAXIMUM CUT SET SIZE =  3

CUT SETS FOR INJ TO PERSONNEL OR FACILITY DAMAGE

CUT SET #  1
DB1            RND OUTSIDE STRUCTURE                       0.300D-02
DB3            PSNL IN VCNTY OF DET.                       0.100D-01
DB5            RND DET                                     0.100D-03
CUT SET RATE = 0.300E-08

CUT SET #  2
DB1            RND OUTSIDE STRUCTURE                       0.300D-02
DB3            PSNL IN VCNTY OF DET.                       0.100D-01
DB6            FRGMT W/  79 JOULES                         0.100D-02
CUT SET RATE = 0.300E-07

CUT SET #  3
DB1            RND OUTSIDE STRUCTURE                       0.300D-02
DB4            IN PTH OF FRGMT                             0.750D-02
DB5            RND DET                                     0.100D-03
CUT SET RATE = 0.225E-06

CUT SET #  4
DB1            RND OUTSIDE STRUCTURE                       0.300D-02
DB4            IN PTH OF FRGMT                             0.750D-02
DB6            FRGMT W/  79 JOULES                         0.100D-02
CUT SET RATE = 0.225E-07

CUT SET #  5
DB2            RND THROWN FM STRUCTURE                     0.100D-02
DB3            PSNL IN VCNTY OF DET.                       0.100D-01
DB5            RND DET                                     0.100D-03
CUT SET RATE = 0.100E-08

CUT SET #  6
DB2            RND THROWN FM STRUCTURE                     0.100D-02
DB3            PSNL IN VCNTY OF DET.                       0.100D-01
DB6            FRGMT W/  79 JOULES                         0.100D-02
CUT SET RATE = 0.100E-07

CUT SET #  7
DB2            RND THROWN FM STRUCTURE                     0.100D-02
DB4            IN PTH OF FRGMT                             0.750D-02
DB5            RND DET                                     0.100D-03
CUT SET RATE = 0.750E-09

CUT SET #  8
DB2            RND THROWN FM STRUCTURE                     0.100D-02
DB4            IN PTH OF FRGMT                             0.750D-02
DB6            FRGMT W/  79 JOULES                         0.100D-02
CUT SET RATE = 0.750E-08

*****   END OF CUT SET LIST FOR SIZES 1 THRU  3   *****

***** CALCULATED TOP EVENT RATE = 0.770E-07 *****
```

Culling those fault events that occur most frequently in the cut sets can reduce the likelihood of the head event. By changing the probability of the culled events, their occurrence can be controlled or eliminated. To change the probability of an event implies a change in state or condition. This can be accomplished by employing an engineering modification, a simple procedural change, or a warning device. This technique can be used to eliminate single point failures when they occur.

APPENDIX C. REFERENCE

Shipe, R.B., Lucas T.A., Methodology Investigation, Final Report of Assessment, Fault Tree Analysis, and Solution of Ammunition Kickout Problem, AD No. B141266L, May 1989.

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